Wakefield Acceleration: from Laboratory to Cosmos

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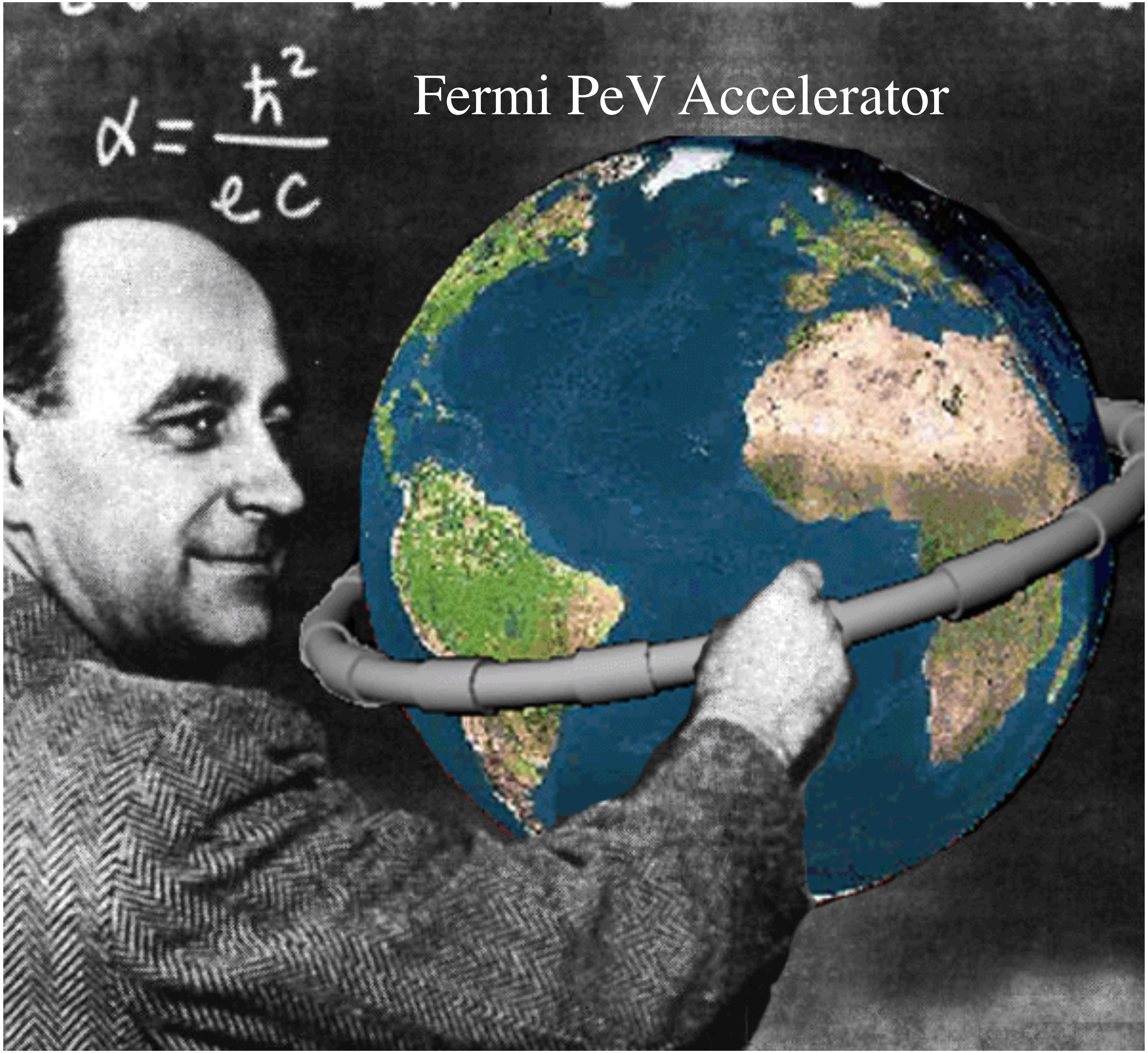
Special thanks to JSPS for my fellowship in 1973 (the first year JSPS established it after the Fulbright Fellowship was discontinued for Japan)

Collaboration: G. Mourou, K. Nakajima, S. Bulanov, T. Esirkepov, J. Koga, M. Kando, A. Suzuki, M. Nozaki, T. Saeki, T. Ebisuzaki, A. Mizuta, X. Yan, M. Zhou, A. Chao, K. Abazajian, N. Canac, X. M. Zhang, D. Farinella, P. Taborek, F. Dollar, P. Grabowski, M. Spiro, R. Heuer, A. Caldwell, B. Holzer, F. Albert, L.M. Chen, P.S. Chen, N. Zamfir, C. Barty, M. Downer, J. Wheeler, Y.M. Shin, N. Naumova

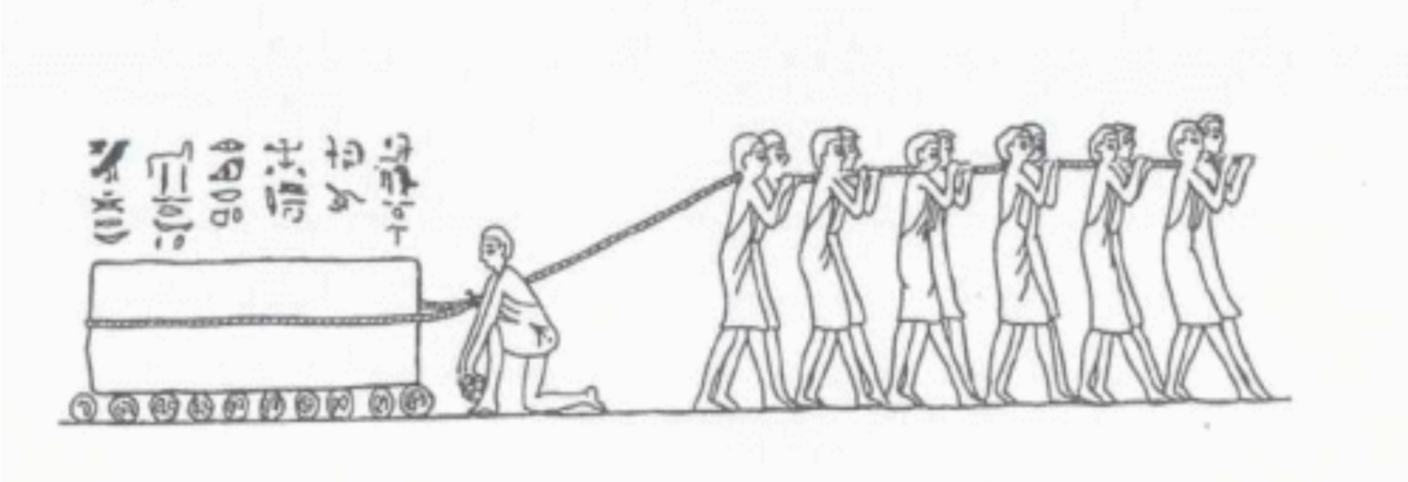
- Introduction: a disruptive idea
- Ascent toward 100GeV and collider
- Single-cycled laser and "TeV on a chip"
- Nature's favorite acceleration: cosmic wakefield


$\alpha = \frac{\hbar^2}{ec}$
Fermi PeV Accelerator

Plasma collective accelerator
vs conventional linear accelerator

Collective force ~$\boldsymbol{N^2}$ (← linear force ~N)

Coherent and smooth structure



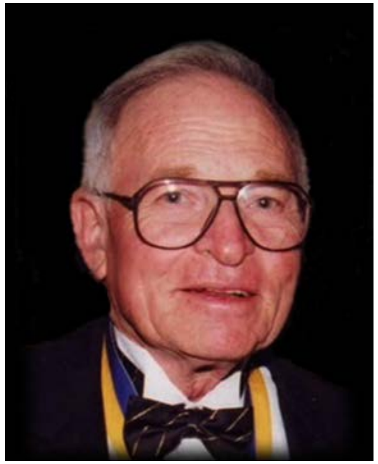
Plasma accelerator driven by laser

compactification by $10^3 – 10^4$ (even by 10^6) over conventional accelerators
enabled by laser technology (intense ultrafast laser compression)

Acceleration by plasma wake waves: History

V. Veksler

Collective acceleration suggested:
Veksler (1956, CERN)
Driven by electron beam
(ion energy)~ (M/m)(electron energy)



N. Rostoker

Many experimental attempts of plasma acceleration (~60's -'70s, Rostoker's lab UCI included)
led to no such amplification
(ion energy)~ (2α+1)x(electron)

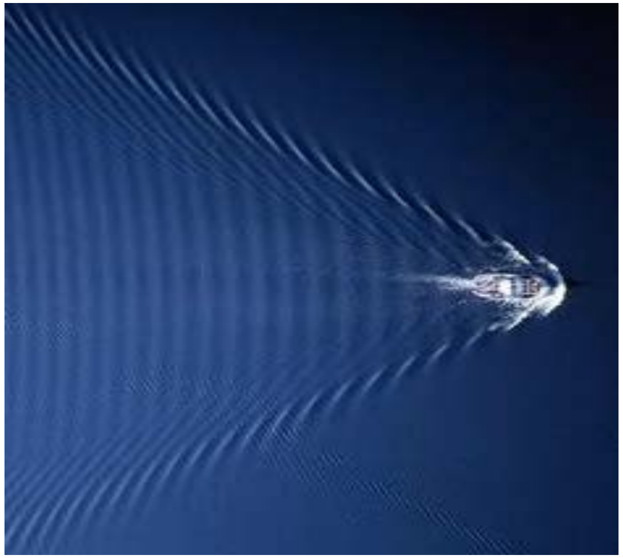
J. Dawson

→ **Tajima-Dawson (1979, UCLA) wakefield**
#2 **electron acceleration** possible
with **trapping** **(with the Tajima-Dawson field)** with laser, more tolerant for sudden process

Laser Wakefield (LWFA):

Wake phase velocity >> water movement speed
maintains **coherent** and **smooth** structure

Tsunami phase velocity becomes ~0,
causes **wavebreak** and **turbulence**

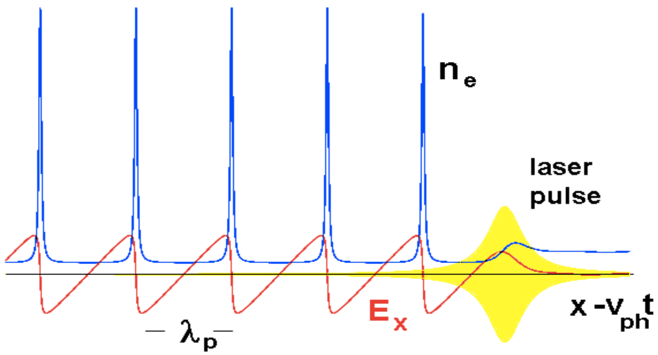


vs

Strong beam (of laser / particles) drives plasma waves to saturation amplitude: $E = m\omega v_{ph}/e$

No wave breaks and wake **peaks** at v≈c

Wave **breaks** at v<c



← relativity regularizes (***relativistic coherence***)

Relativistic coherence enhances beyond the Tajima-Dawson field $E = m\omega_p c/e$ (~ GeV/cm)

The late Prof. Abdus Salam

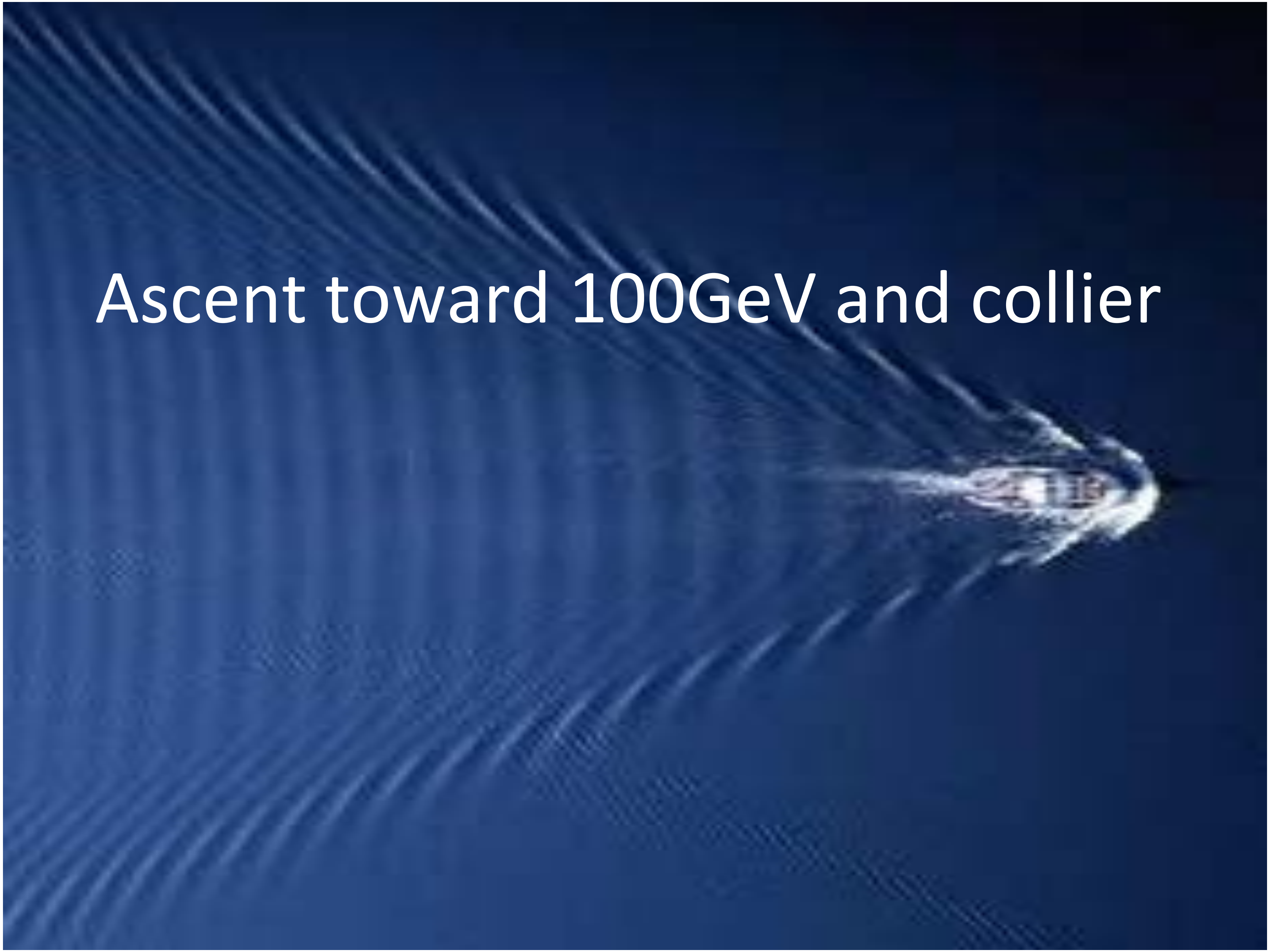
At ICTP Summer School (1981),
Prof. Salam summoned me and discussed
about laser wakefield acceleration.

Salam*: 'Scientists like me began feeling that we had less means to test our theory. However, with your laser acceleration, I am encouraged'.* (1981)

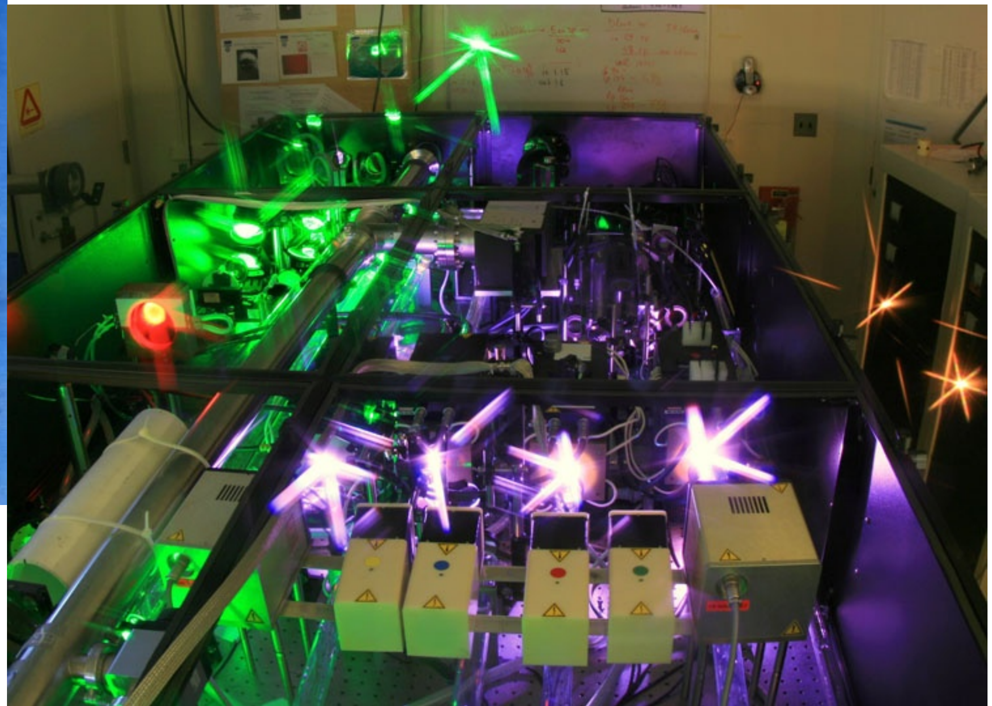
He organized the Oxford Workshop
on laser wakefield accelerator in 1982.

Effort: many scientists over many years to realize his vision / dream
High field science: spawned

Ascent toward 100GeV and collier



Demonstration, realization, and applications of laser wakefield accelerators



(Michigan)

Laser compression method (CPA)
invented in 1985

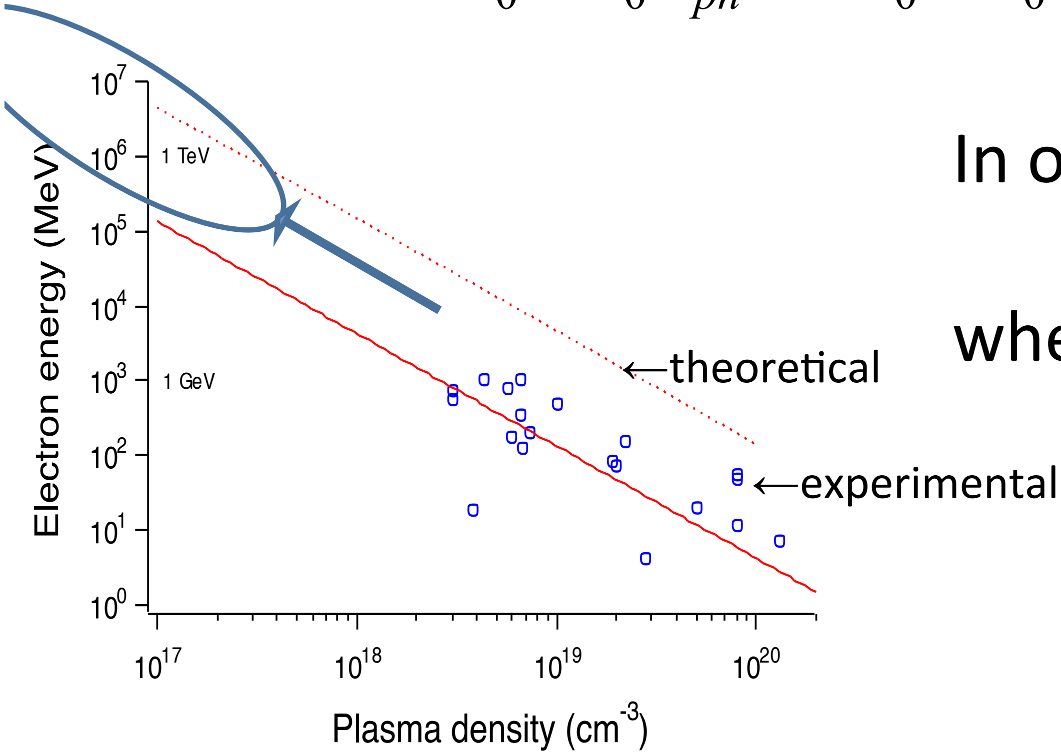
4 GeV laser accelerator LBL

←

3GeV Synchrotron SOLEIL

Theory of wakefield toward extreme energy

$$\Delta E \approx 2m_0c^2a_0^2\gamma_{ph}^2 = 2m_0c^2a_0^2\left(\frac{n_{cr}}{n_e}\right),$$ (when 1D theory applies)



In order to avoid wavebreak,

$$a_0 < \gamma_{ph}^{1/2},$$

where

$$\gamma_{ph} = (n_{cr}/n_e)^{1/2}$$

n_{cr} =10^{21} (1eV photon)
→ 10^{29} (10keV photon)

n_e = 10^{16} (gas) → 10^{23} (solid)

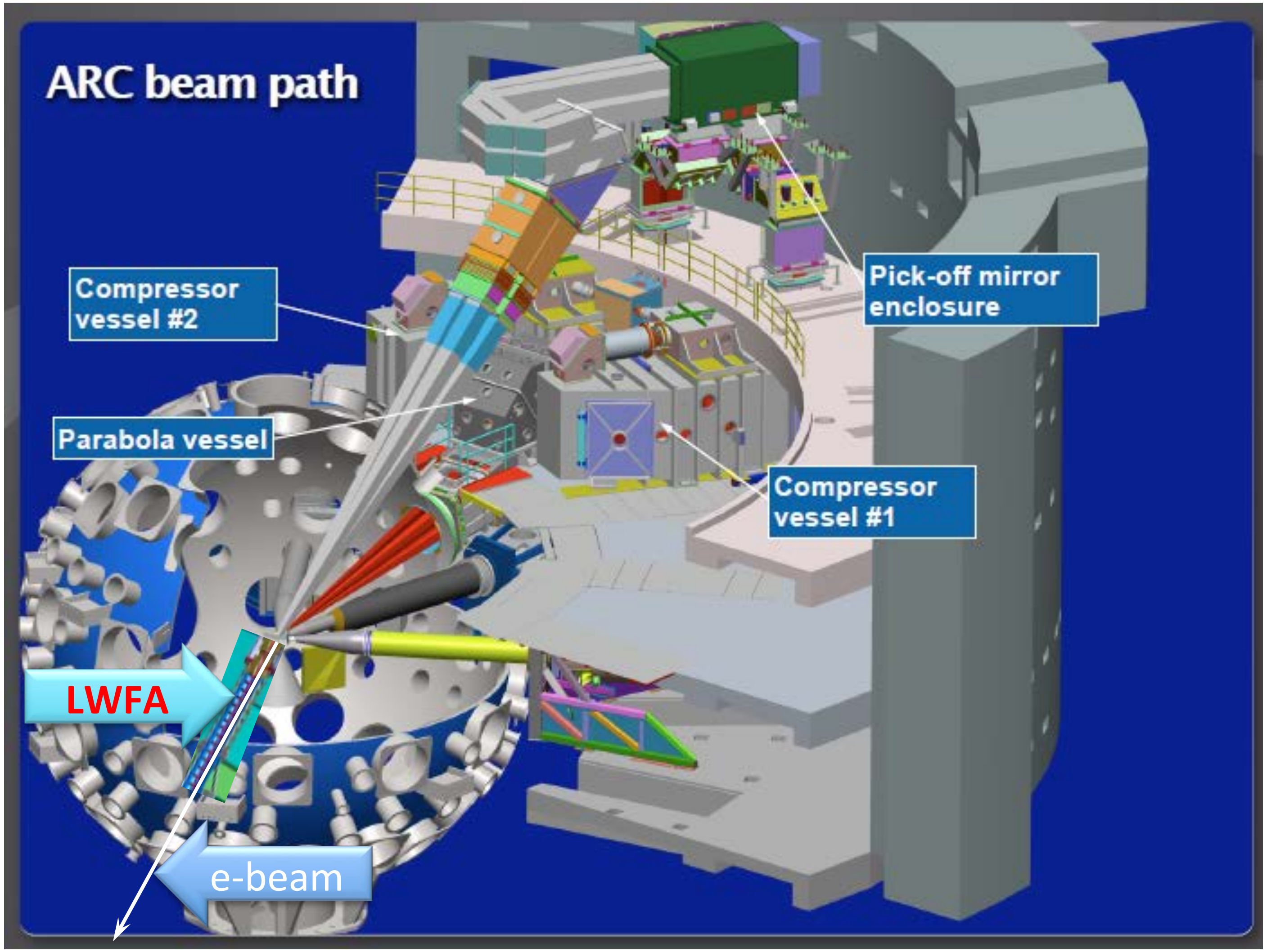
$$L_d = \frac{2}{\pi}\lambda_p a_0^2\left(\frac{n_{cr}}{n_e}\right),$$

dephasing length

$$L_p = \frac{1}{3\pi}\lambda_p a_0\left(\frac{n_{cr}}{n_e}\right),$$

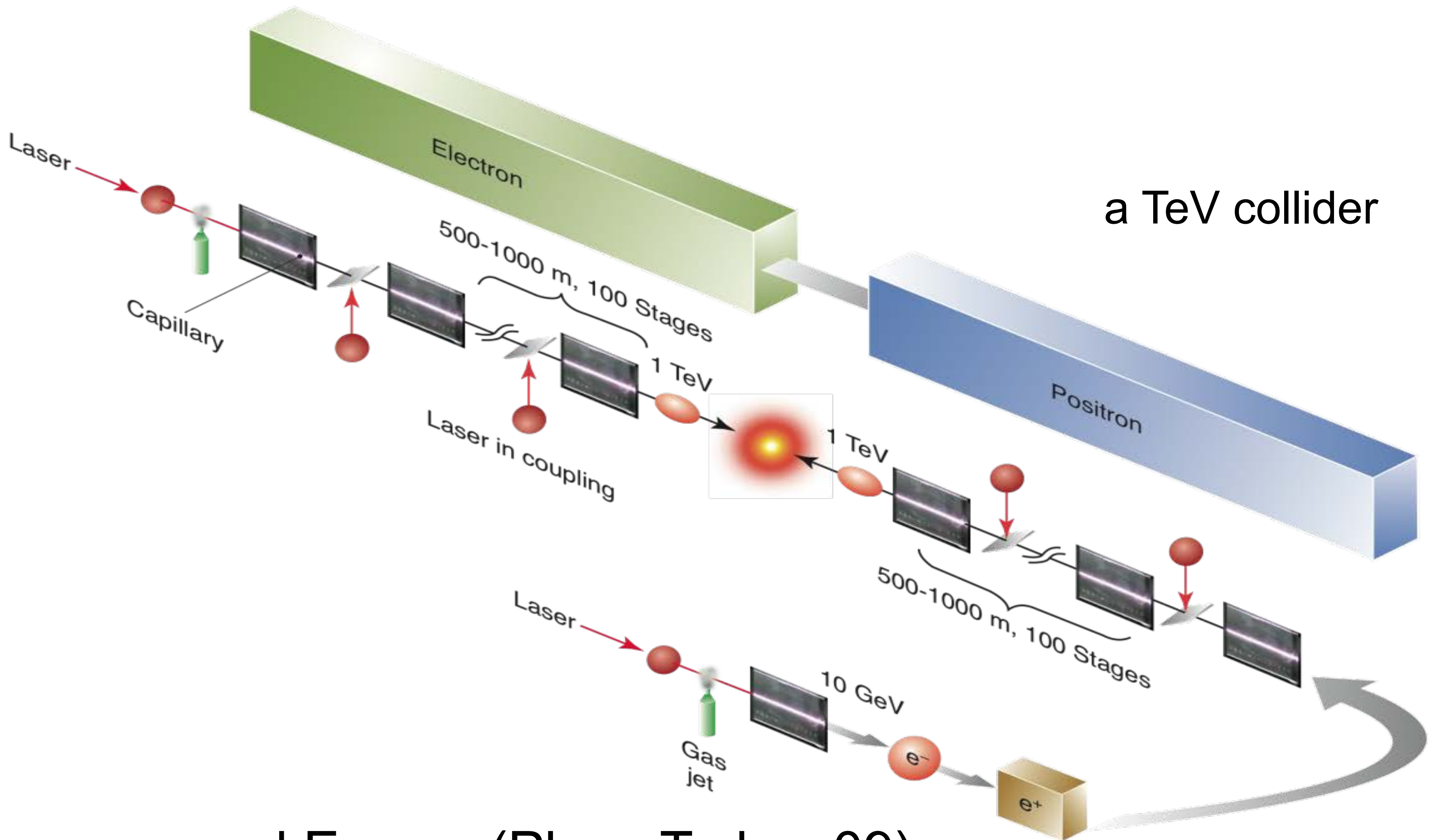
pump depletion length

100 GeV UV LWFA experiment at Livermore



by courtesy of C.P.J. Barty

Laser driven collider concept



a TeV collider

Leemans and Esarey (Phys. Today, 09)

ICFA-ICUIL Joint Task Force on Laser Acceleration(Darmstadt,10)

Density scalings of **LWFA** for collider

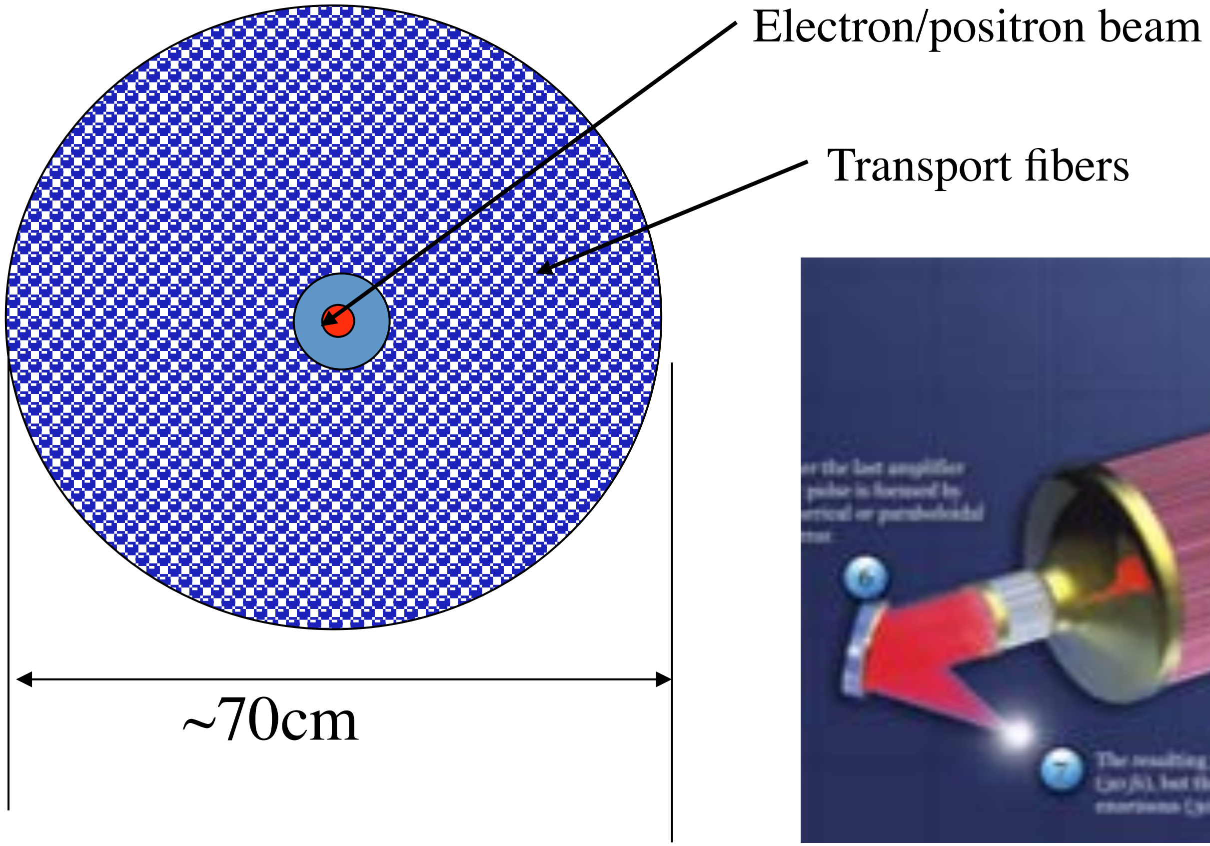
Accelerating field E_z	$\propto n_e^{1/2}$
Focusing constant K	$\propto n_e^{1/2}$
Stage length L_{stage}	$\propto n_e^{-3/2}$
Energy gain per stage W_{stage}	$\propto n_e^{-1}$
Number of stages N_{stage}	$\propto n_e$
Total linac length L_{total}	$\propto n_e^{-1/2}$
Number of particles per bunch N_b	$\propto n_e^{-1/2}$
Laser pulse duration τ_L	$\propto n_e^{-1/2}$
Laser peak power P_L	$\propto n_e^{-1}$
Laser energy per stage U_L	$\propto n_e^{-3/2}$
Radiation loss $\Delta\gamma$	$\propto n_e^{1/2}$
Radiative energy spread σ_γ/γ_f	$\propto n_e^{1/2}$
Initial normalized emittance ε_{n0}	$\propto n_e^{-1/2}$
Collision frequency f_c	$\propto n_e$
Beam power P_b	$\propto n_e^{1/2}$
Average laser power P_{avg}	$\propto n_e^{-1/2}$
Wall plug power P_{wall}	$\propto n_e^{1/2}$

(Nakajima, PR STAB, 2011)

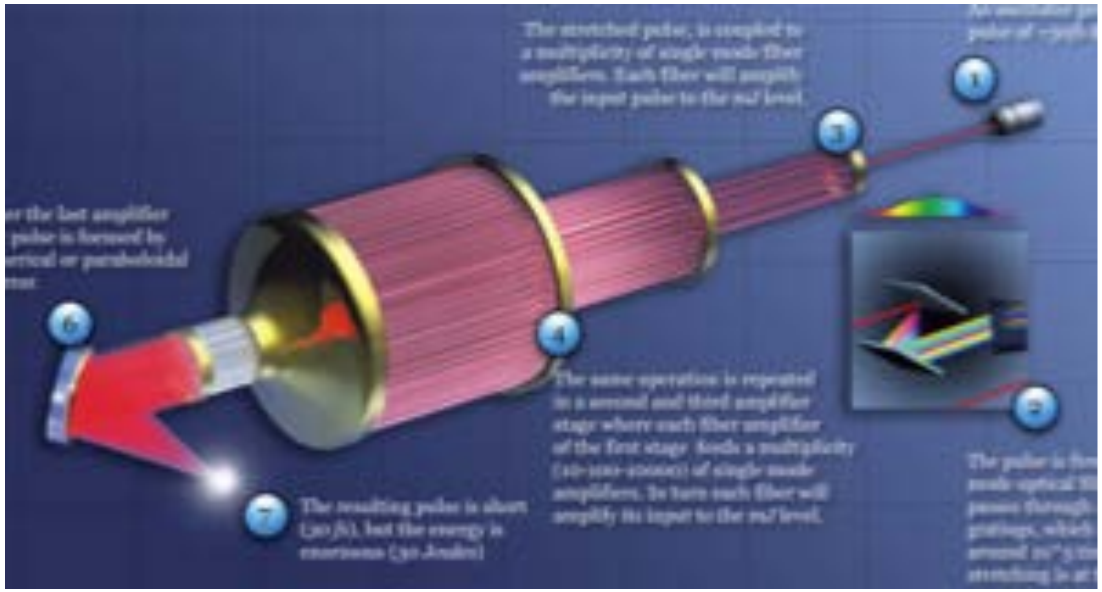
10^{18} /cc (conventional) → 10^{16} /cc

CAN Laser:

Need to Phase
32 J/1mJ/fiber~ 3×10^4 Phased Fibers!

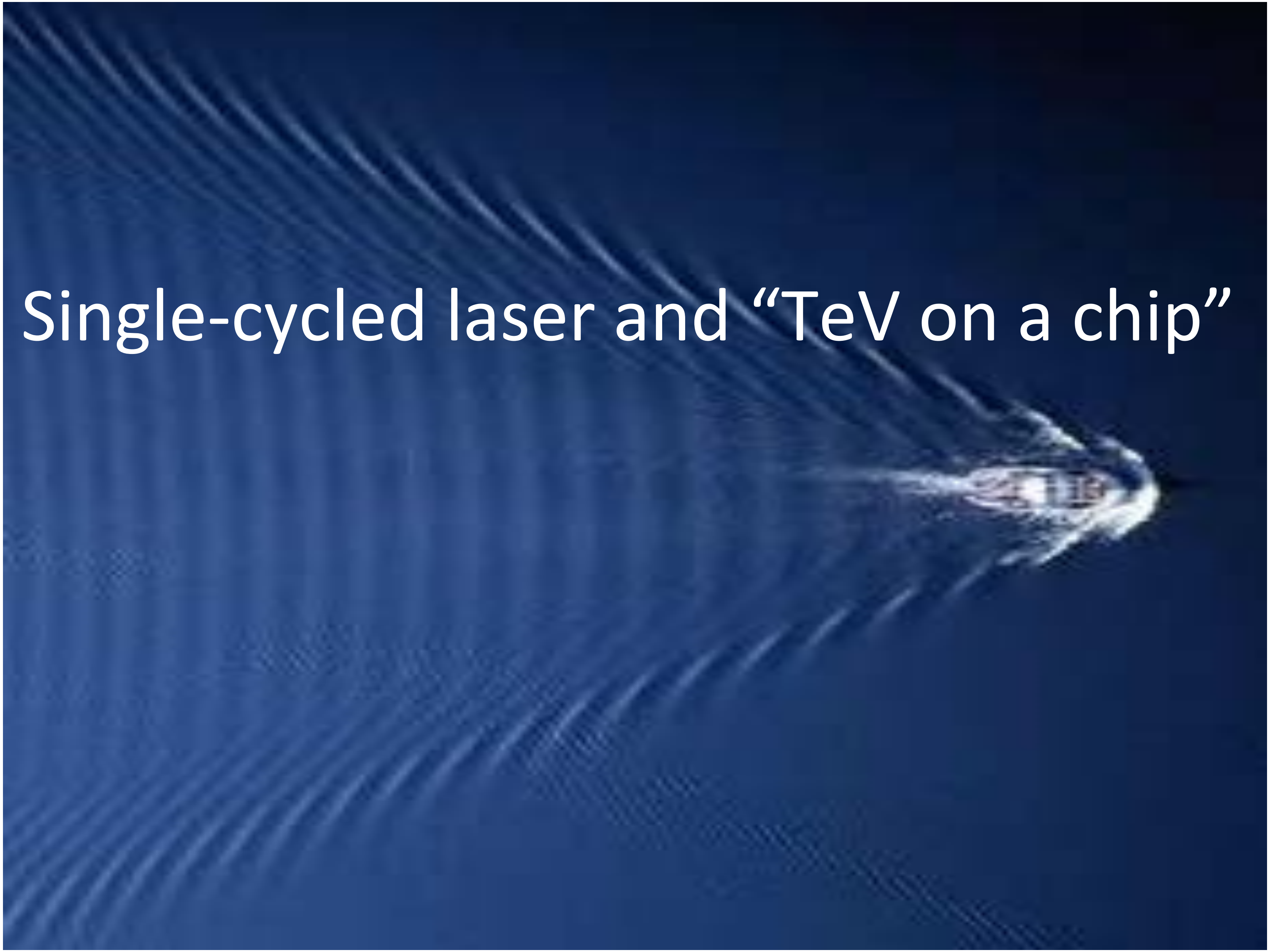


G. Mourou: patent (2005)
Mourou et al. patent (2012)

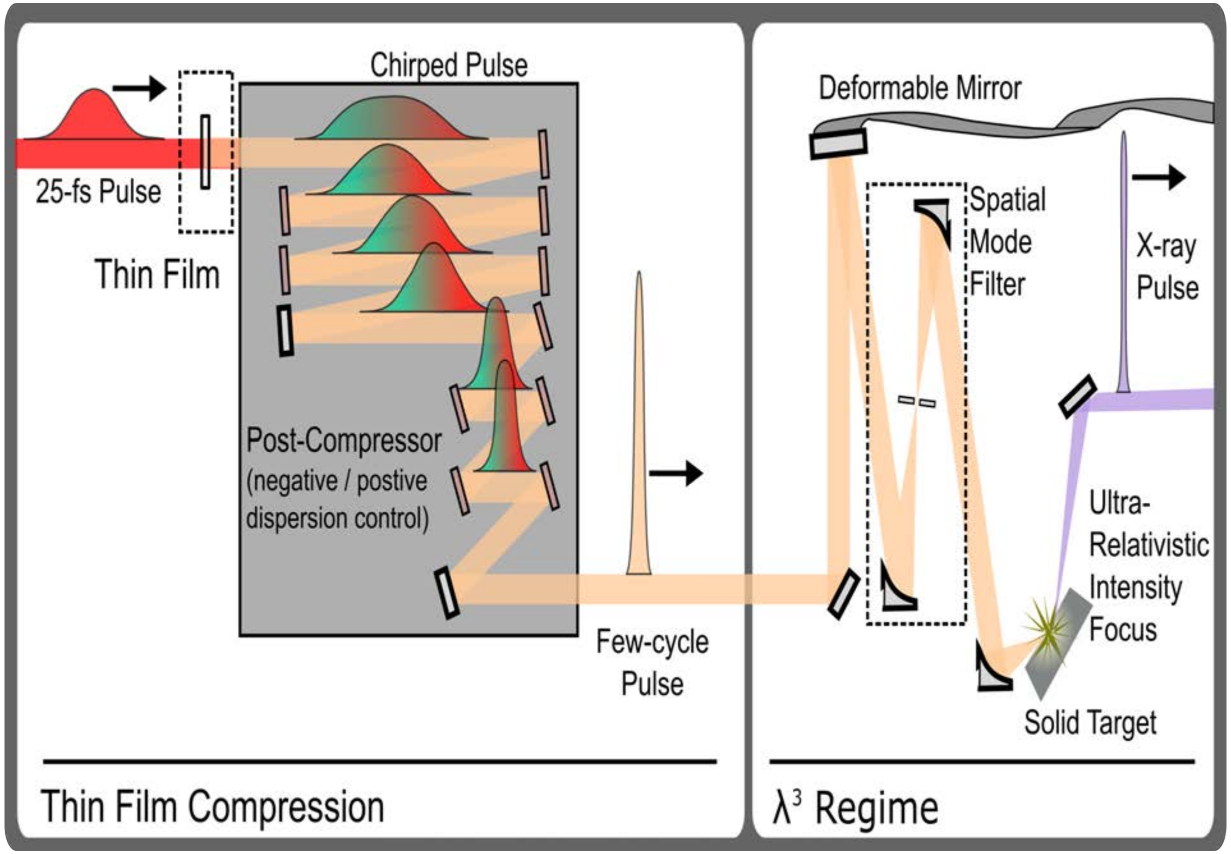


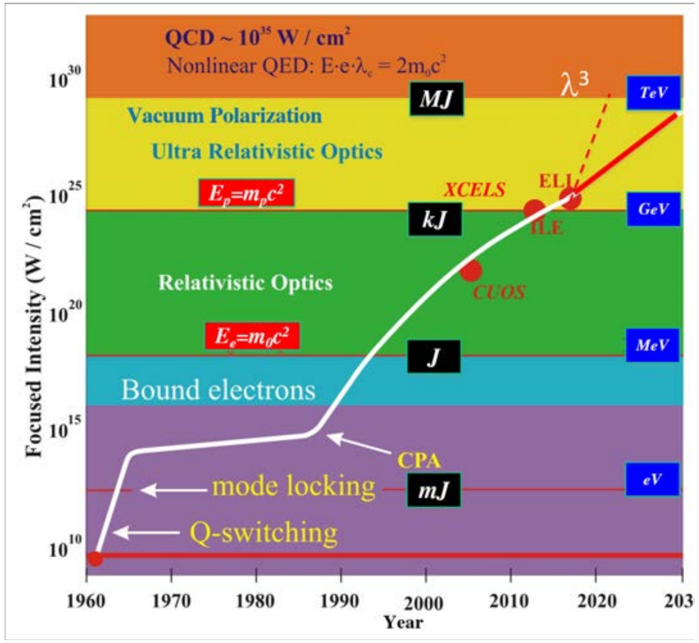
Length of a fiber ~2m   Total fiber length~ $5\ 10^4$km

Single-cycled laser and “TeV on a chip”



Thin film compression and single-cycle optical and X-ray lasers





G. Mourou et al. (2014)

X-ray LWFA in crystal suggested

X-ray Laser Wakefield Accelerator in crystal:

LWFA pump-depletion length:

$$L_{acc} \sim a_X\, (c/\omega_p)\, (\omega_X/\omega_p)^2, \qquad (a_X = eE_X/mc\omega_X)$$

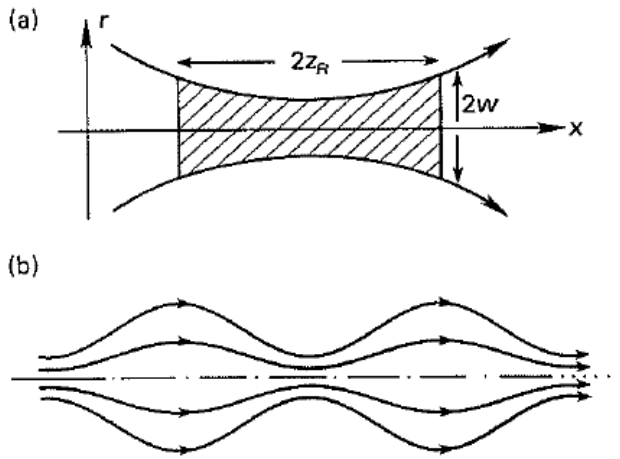
LWFA energy gain

$$\varepsilon_X = 2a_X^2\, mc^2 (n_{cr}/n_e),$$

Here, $n_{cr} = 10^{29}$, $n_e = 10^{23}$, $a_X \sim 30$ (pancake laser pulse with the Schwinger intensity, with focal radius assumed the same as optical laser radius. Could be greater if we further focus by optics, or nonlinearity, or if we not limit the intensity at Schwinger. see below)

The vacuum self-focus power threshold

$$P_{cr} = (45/14)\, c\, E_S^2\, \lambda^2 \alpha^{-1}, \qquad (E_S: \text{Schwinger field})$$



Schwinger fiber acceleration in vacuum:

(no surface, no breakdown)

Vacuum photon dispersion relation with focus

$$\omega = c\sqrt{(k_z^2 + \langle k_{perp}^2 \rangle)},$$

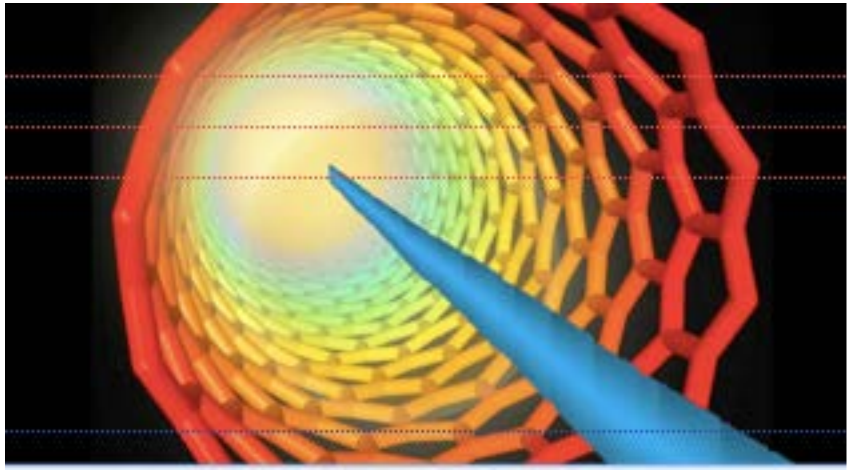
The vacuum dispersion relation with fiber self-modulation

$$\omega / (k_z + k_s) = c, \qquad (k_s = 2\pi / s)$$

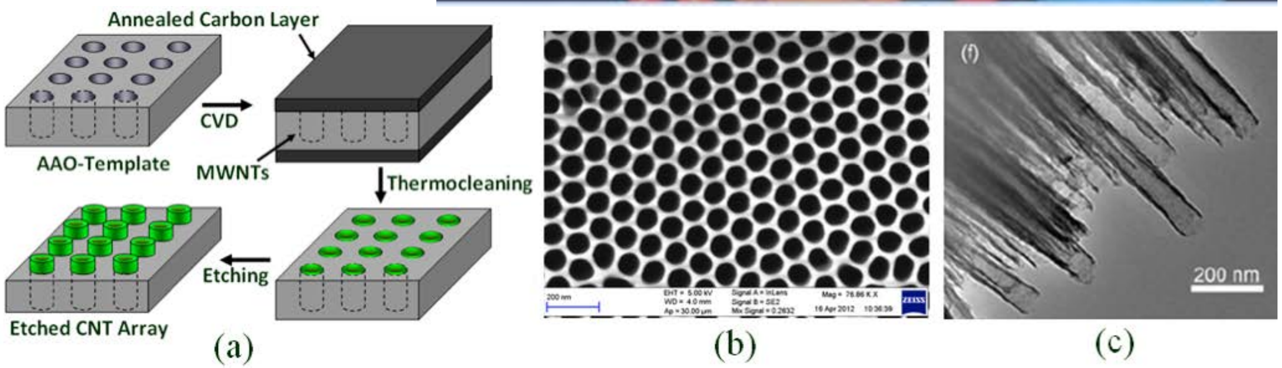
(Tajima and Cavenago, PRL, 1987)

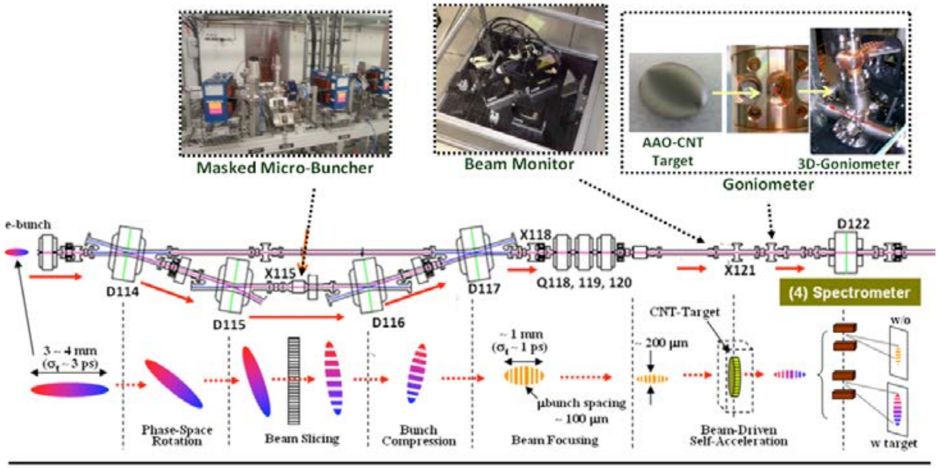
Wakefield acceleration in porous nanomaterials

Carbon nanotube with
Particle beam / X-ray pulse



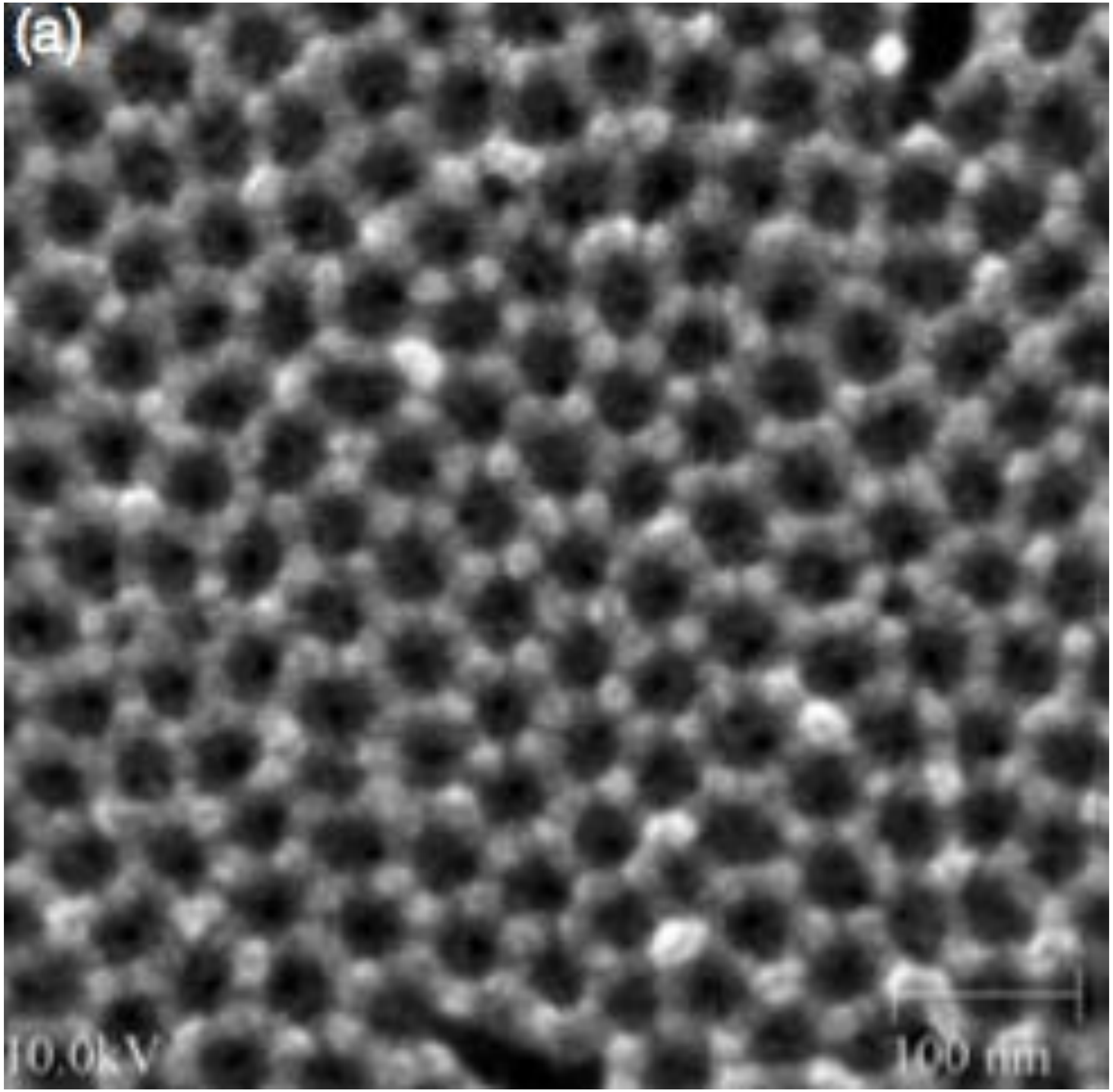
Porous nanomaterial





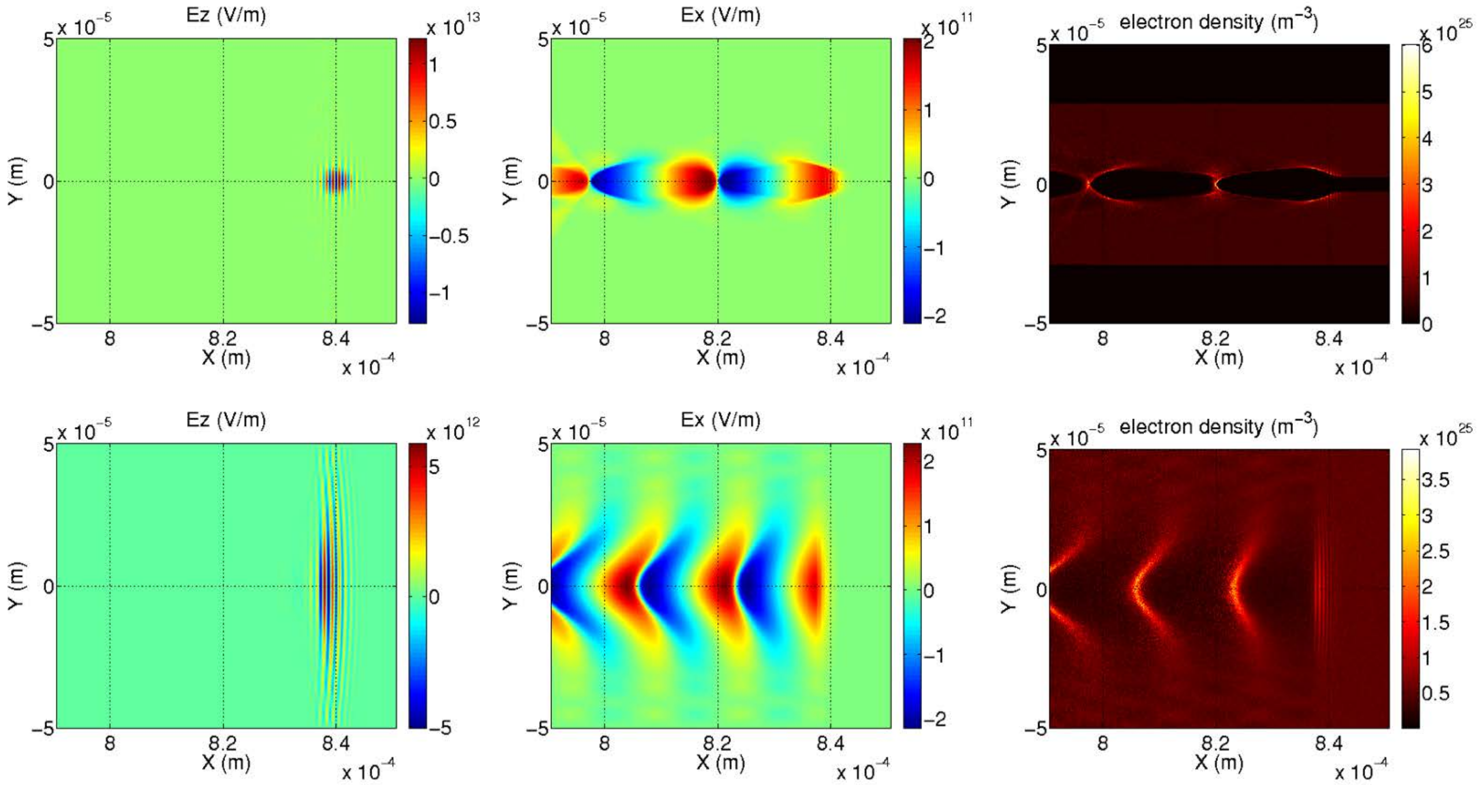
Collaboration (2015) with Fermilab / NIU
Y. Shin et al.

Porous Nanomaterial



Porous alimina on Si substrate
Nanotech. **15**, 833 (2004)

X-ray LWFA in a tube vs. uniform solid

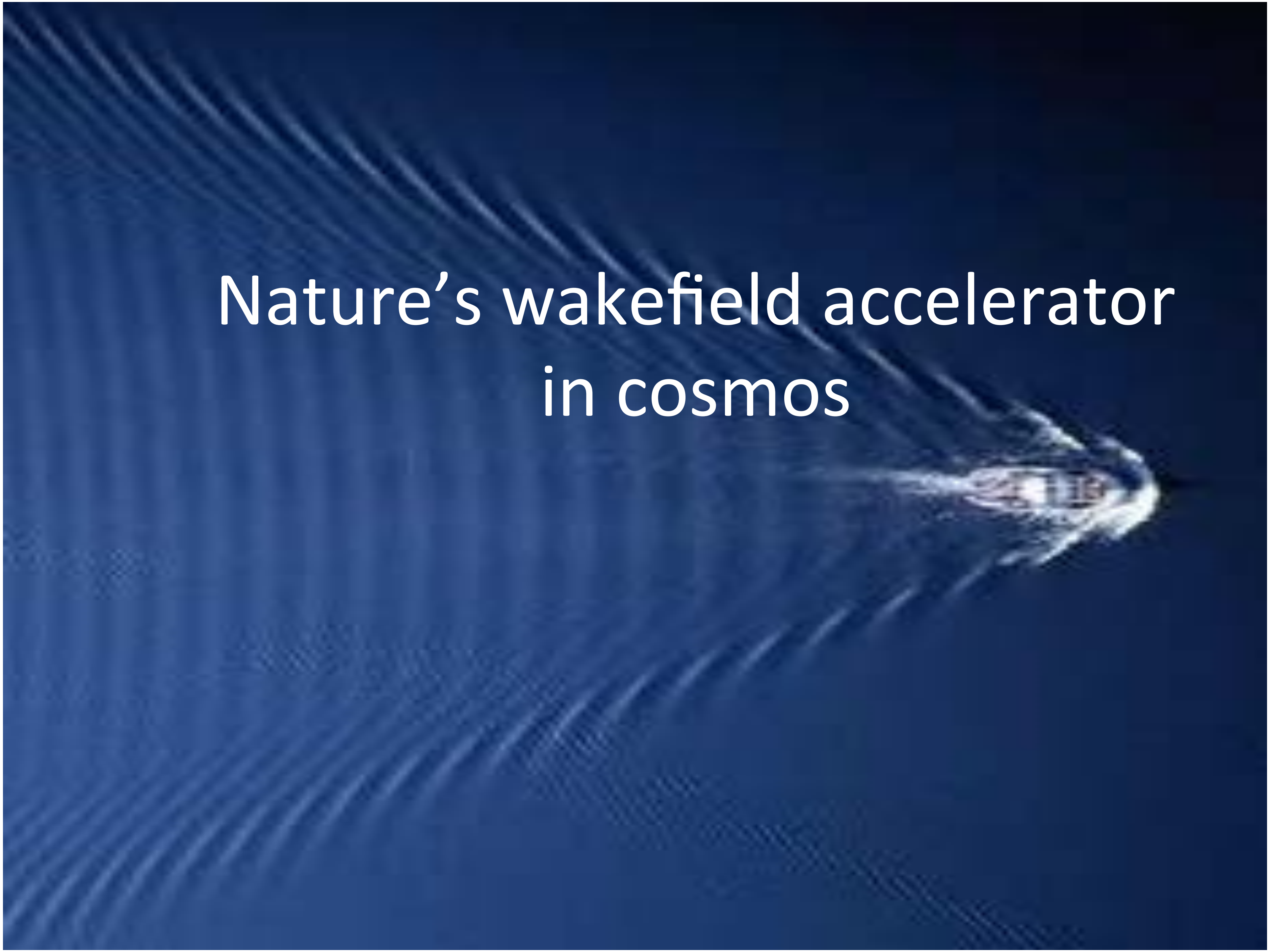


in nanotube

in uniform solid

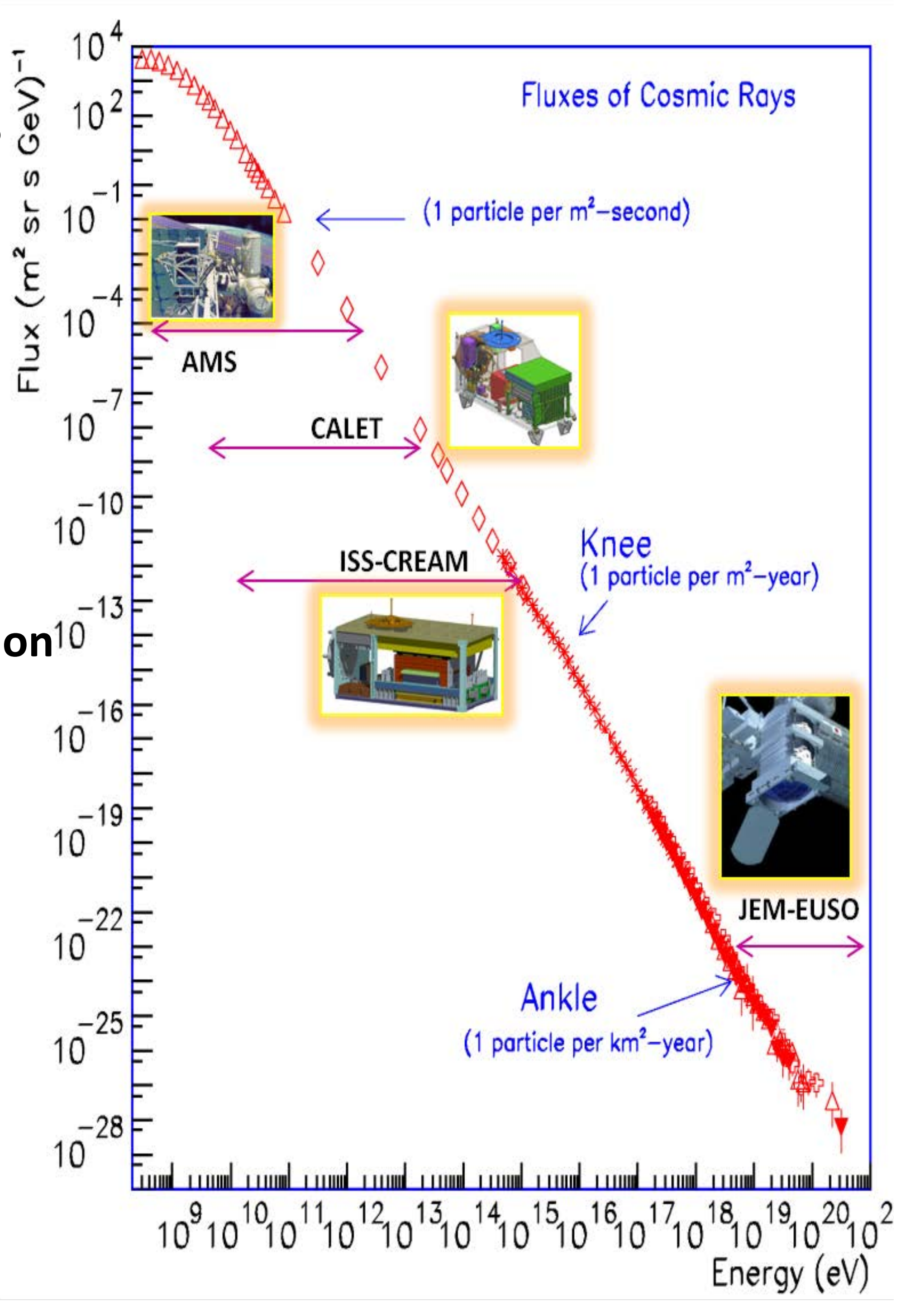
A few-cycled 1keV X-ray pulse (a_0 ~ O(1)), causing 10TeV/m wakefield in the tube
more strongly confined in the tube
cf: uniform solid

X. Zhang


Nature’s wakefield accelerator
in cosmos

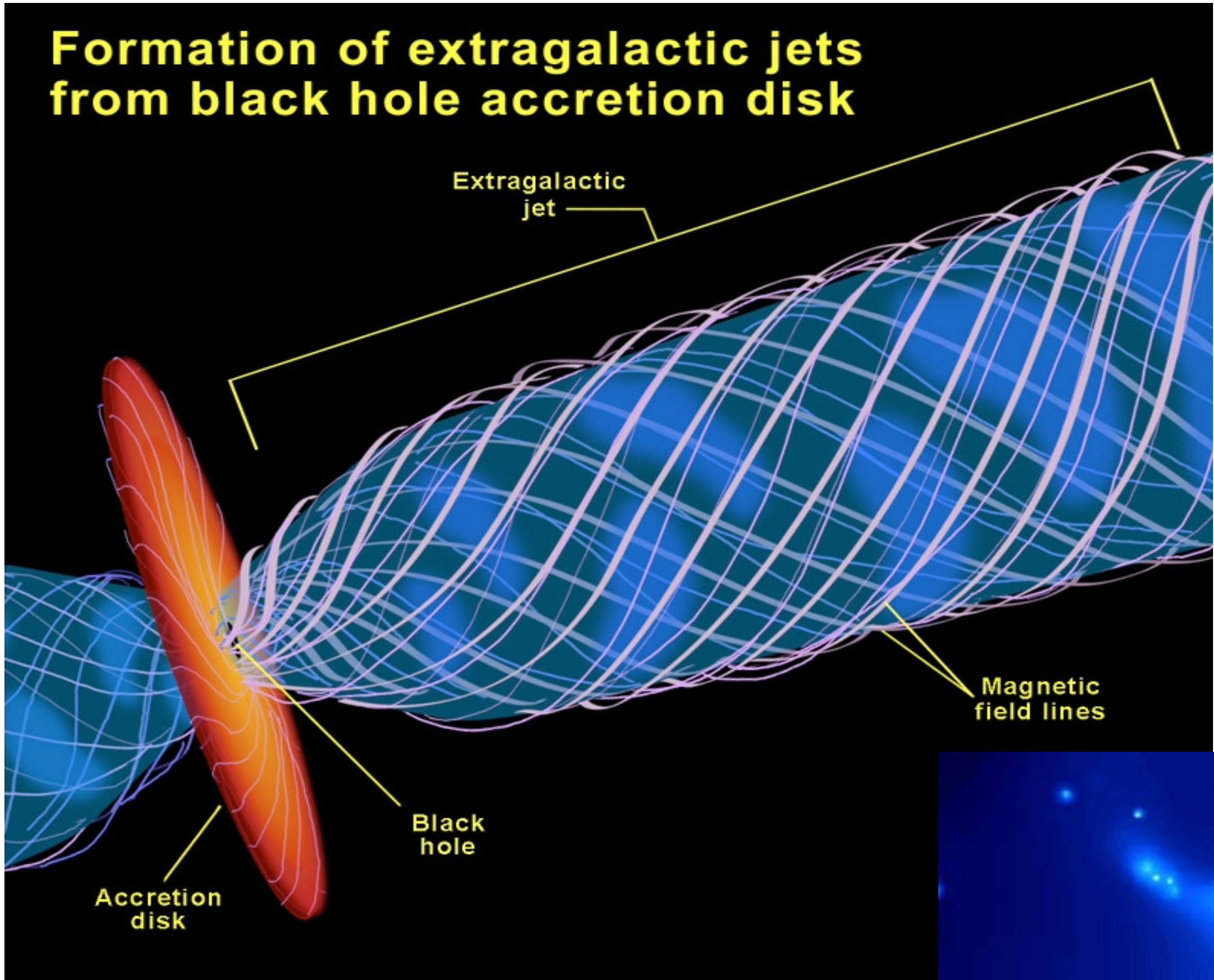
Ultrahigh Energy Cosmic Rays (UHECR)

- Fermi mechanism runs out of steam
  - beyond 10^{19} eV
  - due to synchrotron radiation
- Wakefield acceleration
  - comes in rescue
  - prompt, intense, linear acceleration
  - small synchrotron radiation
  - radiation damping effects?



Cen A

- Distance : 3.4Mpc
- Radio Galaxy
  - Nearest
  - Brightest radio source
- Elliptical Galaxy
- Black hole at the center w/ relativistic jets

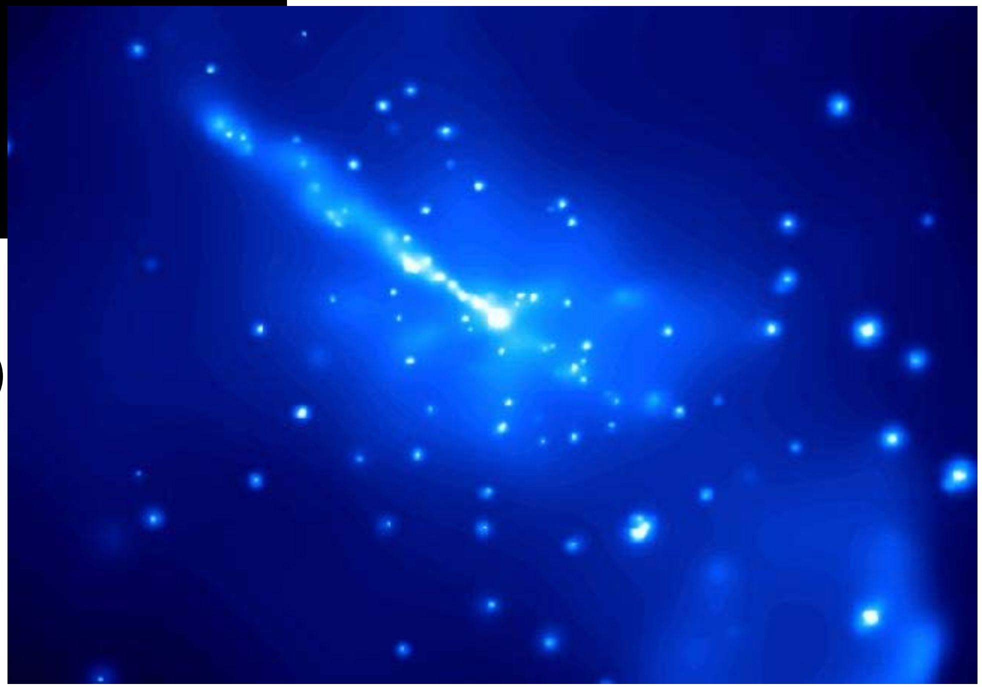


Fermi's '**Stochastic Acceleration**'
(large synchrotron radiation loss)

↓

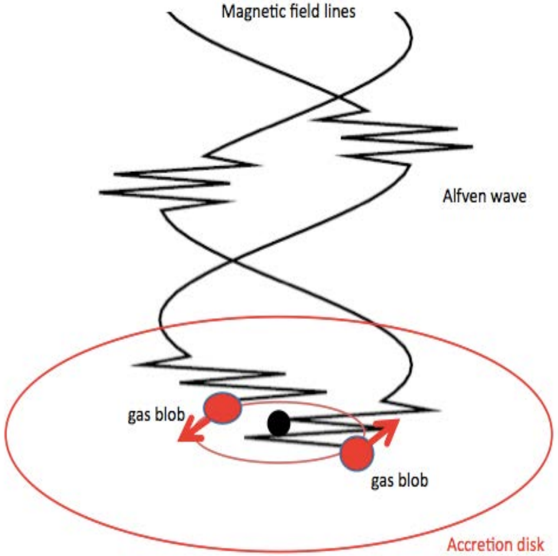
Coherent wakefield acceleration
(no limitation of the energy)

Nature's LWFA : Blazar jets
extreme high energy cosmic rays (~10^{21} eV)
episodic γ-ray bursts observed
consistent with LWFA theory



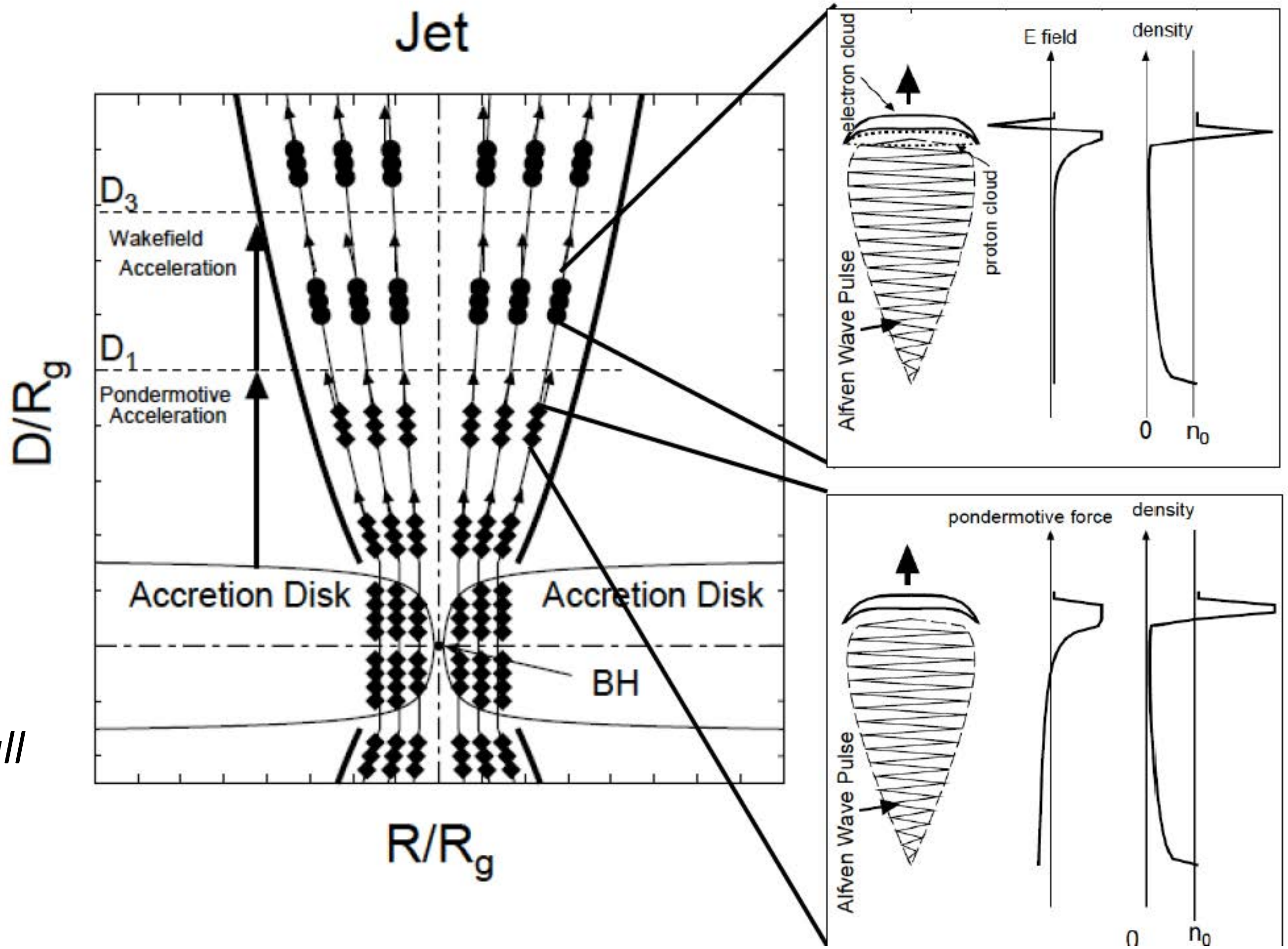
Ebisuzaki-Tajima (2014); Canac, Abazajian, Tajima(2015)

Astrophysical wakefield acceleration: Superintense Alfven Shock in the Blackhole Accretion Disk toward ZeV Cosmic Rays (a_0 ~ 10^6 -10^{10}, large spatial scale)



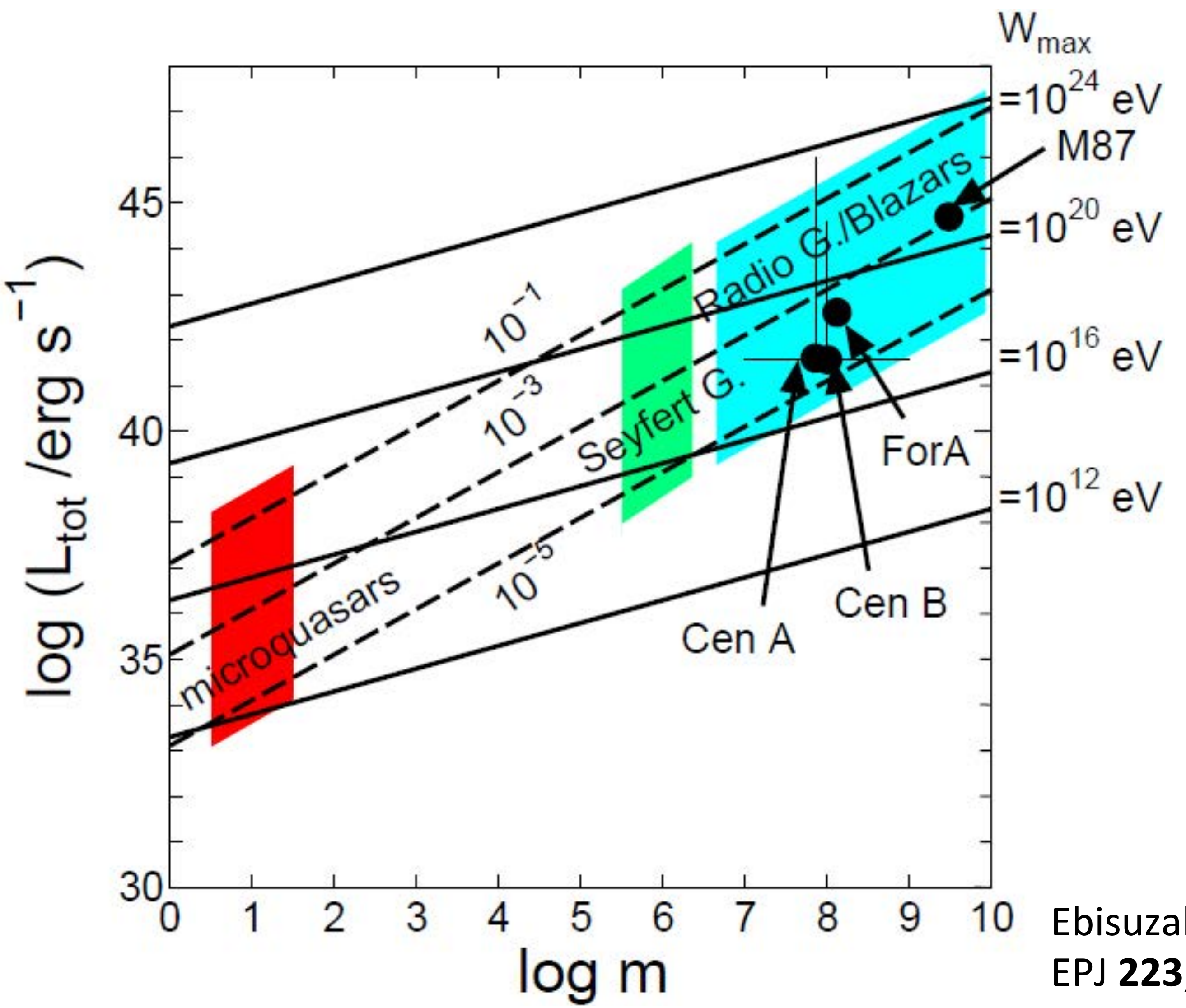
$$a_0 = eE_0 / mc\omega_0 >> 1$$

E_0: modest
ω_0: *extremely small*



Ebisuzaki and Tajima, Astropart. Phys.(2014)

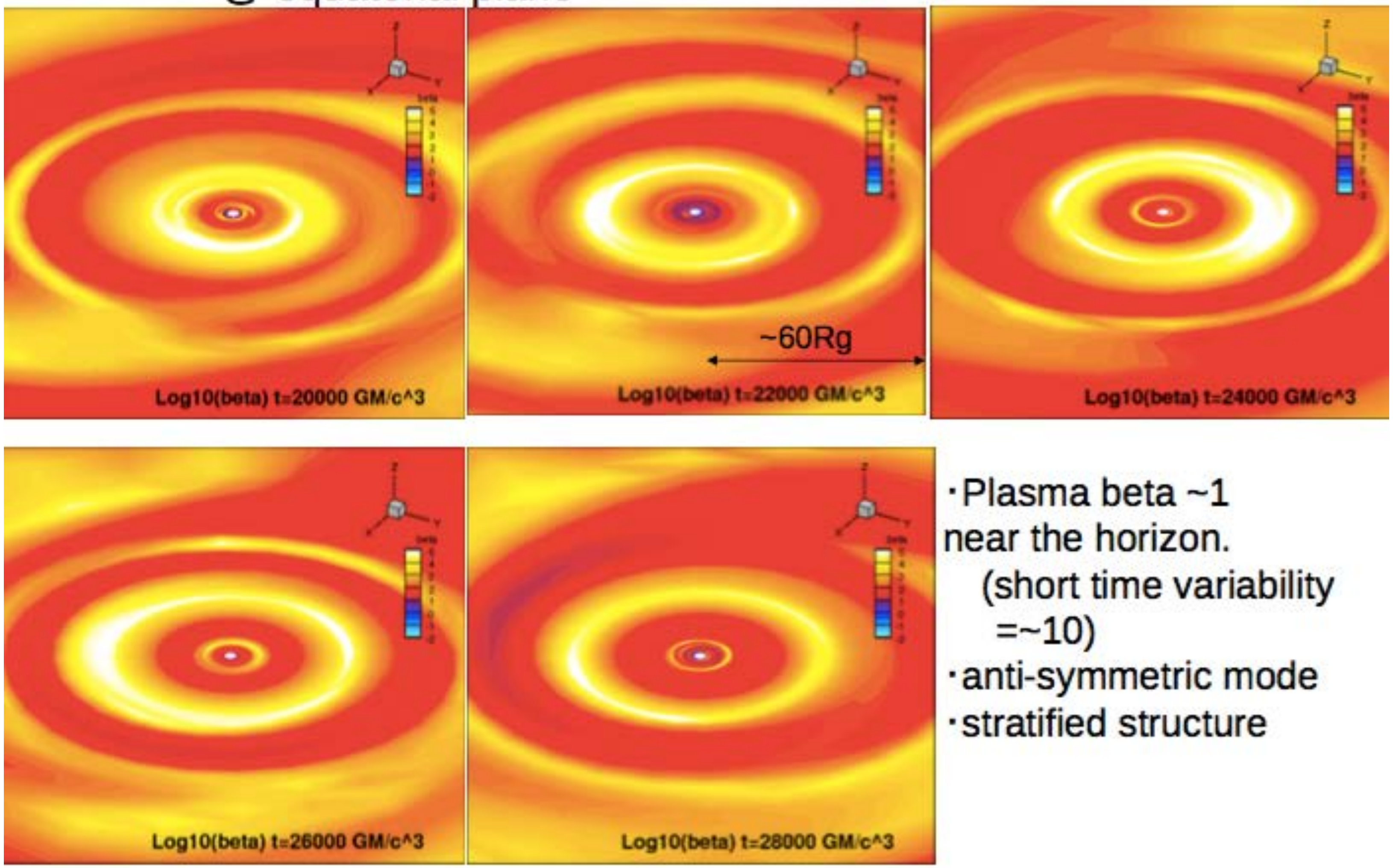
Comic ray acceleration and γ-ray emission: Summary



Ebisuzaki, Tajima
EPJ **223**, 1113(2014)

General Relativistic MHD simulation of accretion disk + jets

Time evolution log10(plasma beta=P_{Gas}/P_{Mag})
@ equatorial plane



- Plasma beta ~1 near the horizon.
  (short time variability =~10)
- anti-symmetric mode
- stratified structure

A. Mizuta, T. Ebisuzaki

General Relativistic MHD simulation of accretion disk + jets

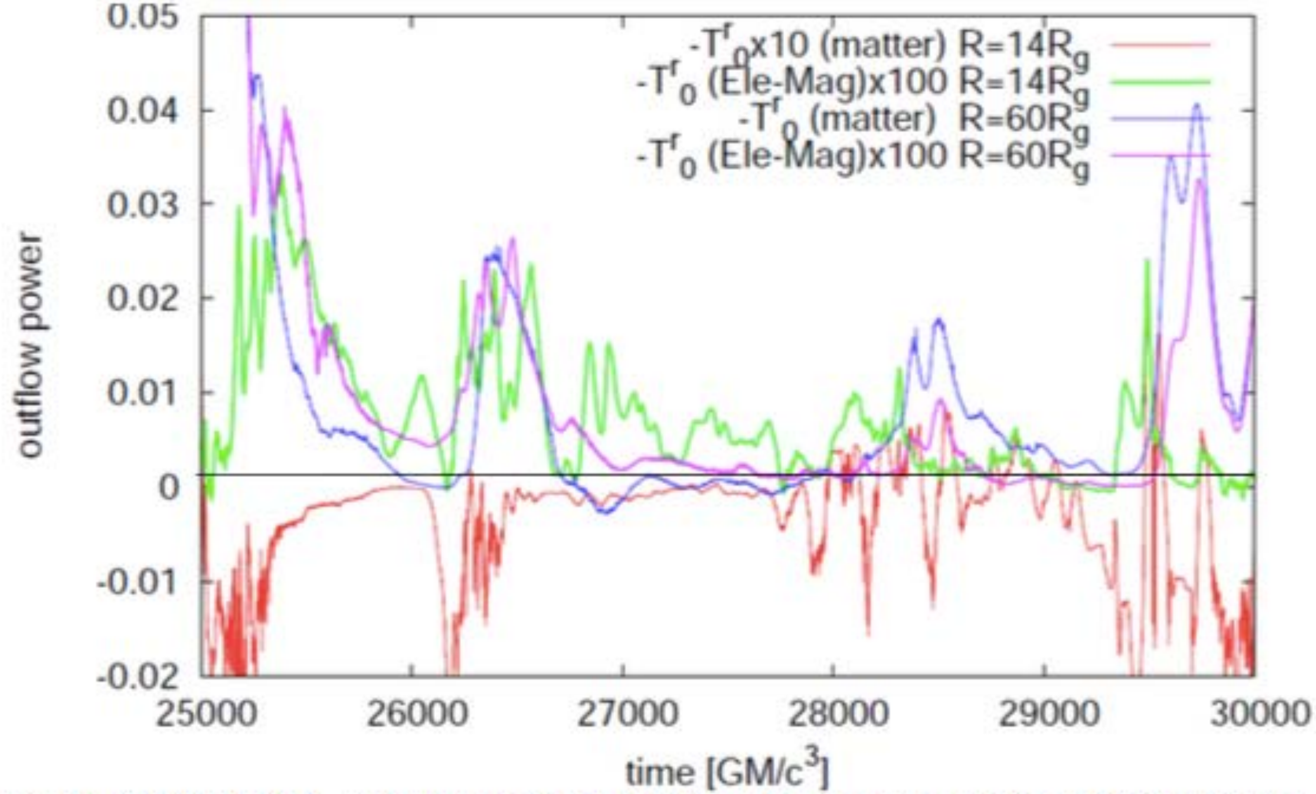
Outflow luminosity (0<θ<10°)

$$E_{\rm dot} = -\int_{\theta=\theta_0}^{\theta=\theta_1}\int_{\phi=0}^{\phi=2\pi}\sqrt{-g}T^r_t\,dA$$

$\theta_0=0$

$\theta_1=10$

outflow power $14R_g$, $60R_g$



Short time variavilitry (Δt~a few tensGM/c³) in electromagnetic components (green and pink) : Good agreement with Ebisuzaki & Tajima(2014) $t_{var} \sim M$

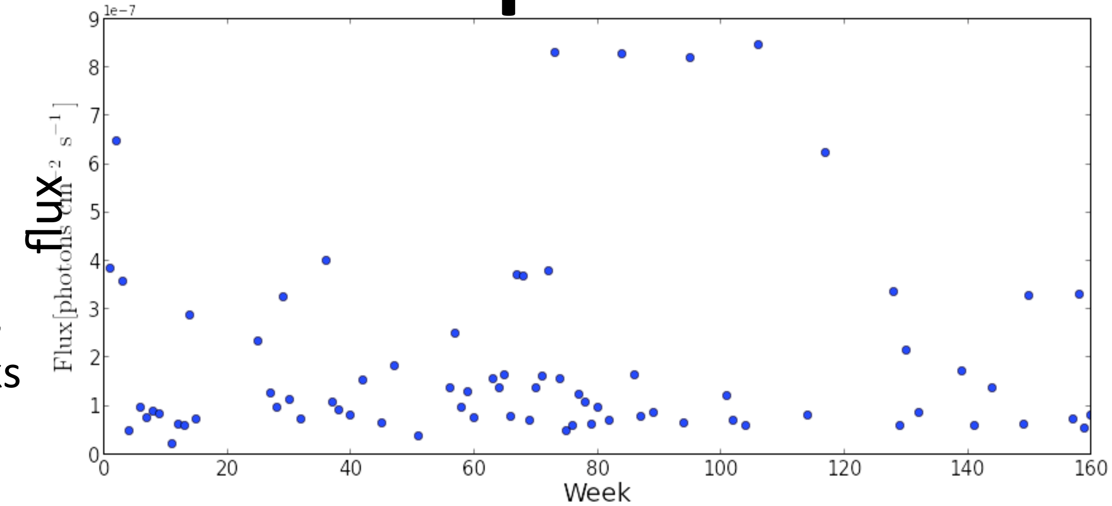
=> possible origine for flares in blazars,

strong Alfven wave mode => Application t wake field acc. for UHECRs

A. Mizuta, T. Ebisuzaki

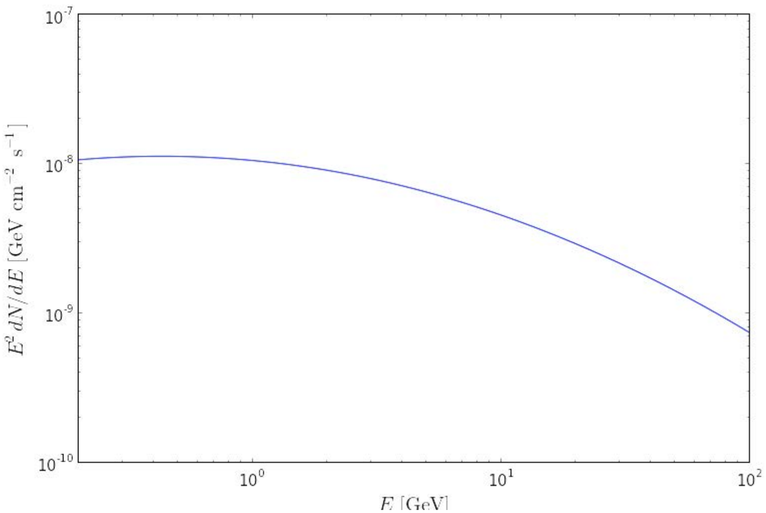
Blazar shows anti-correlation between γ burst flux and spectral index

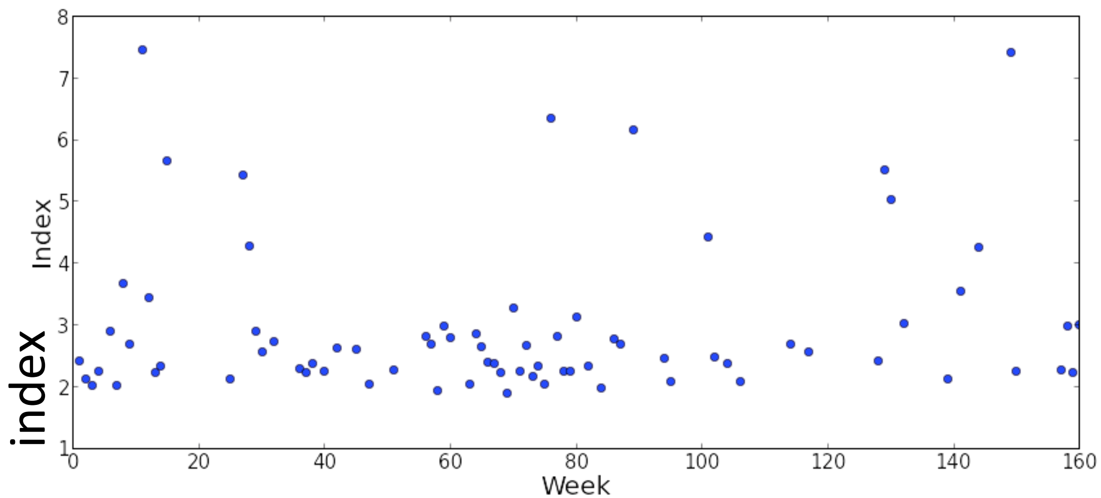
Blazar: AO0235+164
M ~ 10^8 M_{Sun}



Rise time < week (less than a unit),
Period between bursts ~> 10 weeks
Spectral index => 2
(~ Ebisuzaki/Tajima theory)

→ all quantitatively consistent with Wakefield theory





N. Canac, K. Abazajian

Conclusions

- Demonstrated: Using ultrafast pulses (of laser or particle beams), coherent collective (robust) (broader sense of) wakefield (GeV/cm) excitable, which includes both wakefield and ponderomotive accelerations
- With the emerging single-cycle compression technique and its X-ray laser pulse conversion, wakefield in nanostructure (TeV/m) may be accessible
- Ion ponderomotive acceleration also possible in a certain regime of laser (particularly in single-cycle regime)
- Applications: ultrafast radiolysis, intraoperative electron therapy, compact X-ray sources/XFEL, compact proton therapy, radioisotope generation, ADS,….
- (broader sense of) Wakefield acceleration: Nature's accelerators favored for extreme high energy comic rays, gamma ray bursts


Thank you!
有難うございました。
Y.Shin